

The deceleration of aircraft in overrun accidents from the point of first impact to the end of the wreckage path

David E. Pitfield

School of Civil and Building Engineering, Loughborough University (UK)

D.E.Pitfield@lboro.ac.uk

Received May, 2014

Accepted July, 2015

Abstract

Purpose: This paper outlines previous attempts to model aircraft deceleration and using a newer database containing a greater number of observations tries to refine the model.

Design/methodology: It is noted that data inadequacies still necessitate the estimation of a given acceleration for the aircraft wreckage path, but that there are more opportunities to change the intercept in a regression model to reflect categorical and dummy variables that proxy factors such as runway condition, the degree of control exercised by the pilot during the crash, the speed at the point of first impact (hereafter POFI), headwind, rain, characteristics of the terrain on the wreckage path and aborted take-offs.

Findings: The contribution of some of the explanatory variables can be seen. It is a shame other potential influences are not found to be significant. It is important to understand deceleration so that the wreckage location of aircraft accidents can be understood. This then gives guidance of appropriate runway safety areas.

Originality/value: This is the first time this has been attempted on the expanded accident database.

Keywords: Aircraft overrun accidents; deceleration; regression models; runway safety areas

1. Introduction

It was noted by Kirkland (2001) and Kirkland, Caves, Hirst and Pitfield (2003) that one route to improving the understanding of the location of take-off and landing overrun accidents would be to improve the model of aircraft deceleration. This would help in determining appropriate runway safety areas. Work at the Lawrence Livermore National Laboratory, in particular, Kimura et al. (1996) seems to have been amongst the first to examine post-impact deceleration but where the deceleration was assumed to be constant. This is not usually the case as deceleration forces acting upon the aircraft after overrunning the end of the runway are a function of ground friction (which is in itself a function of the weight of the aircraft exerted through the wheels which is linked to airspeed and lift generated by the aircraft's wings) including rolling resistance of the aircraft and retardation caused by sinking below the ground's surface as well as the braking friction generated, aerodynamic drag (a function of airspeed), engine thrust and energy absorption in collisions with obstacles. Kirkland's basic model of deceleration is detailed below. It is also based on a constant rate, but where adjustments can be made to this to cover surface types and obstacles/water encountered. It should be noted that industry based models of deceleration are based on aircraft design parameters rather than on empirical estimation.

Wong's (2007) thesis is based on a database containing details of overrun accidents, undershoot accidents as well as take-off and crash accidents within 10 km of the runways. It is this database that is analysed again in this paper where an attempt is made to improve the deceleration model focusing on overrun accidents and this builds on the pioneering and original work of Wong (2007) and Wong, Pitfield, Caves and Appleyard (2006, 2009a, 2009b). A sample of take-off overruns is first examined, followed by a larger sample of landing overruns. Variables representing pilot control of a crashing aircraft, runway condition, runway braking condition, wreckage path surface and slope, light condition, temperature, rain, snow, icing, wind speed and direction, point of first impact (POFI) velocity, number of obstacles hit, whether the landing was a go-round or whether the take-off was aborted are all considered. It is hoped that this understanding of deceleration will assist in the causal modelling of wreckage x and y locations of aircraft accidents and subsequently the design of runway safety areas.

2. Data

Wong (2007) identified 52 take-off overruns and 199 landing overruns in the aircraft accident database compiled as part of a research project, funded by the UK Engineering and Physical Science Research Council, covering US accidents of aircraft over 6000 lbs. between 1982 and 2002. Exclusions from the accident data are noted in Wong (2007) and in Table 1. Although Wong's work focused on the frequency of accidents (Wong et al., 2009a) and the factors that

were associated with higher frequencies such as adverse meteorological conditions (Wong et al., 2006), the thesis only used cumulative distributions of accident locations to analyse particular airport case studies (Wong et al., 2009b) to show the frequency and distribution of accidents, given the developed frequency models that challenged runway safety areas. This approach was repeated in the Airports Cooperative Research Program, ACRP 3 (TRB, 2008) and has been applied by Applied Research Associates of Maryland (ARA) to Lester B Pearson Toronto International and San Francisco International Airports. A more recent 'model' of location distributions showing well-behaved cumulative distributions of x and y locations of accidents is given in Ayres et al. (2013).

Remove non US entries.
Remove non fixed wing aircraft entries.
Remove entries for aircraft with certified max gross weight <6000 lbs.
Remove entries with unwanted Federal Aviation Regulations (FAR) parts.
Remove entries occurring in unwanted phases of flight.
Remove all single engine aircraft and all piston engine aircraft entries.
Remove all FAR Part 91 entries with a certified maximum gross weight <12,500 lbs.
Remove entries where aircraft damage and injury levels were minor or less.
Only accidents which directly challenged at least one Airport Safety Area or impacting ground or obstacles within 10 km of the landing or take-off runway threshold. This means that the aircraft has exited from the 'normal' areas of operation on the airfield (i.e. veering off the runway or hitting obstacles on landing or take-off). Cases do not have to include fatalities or hull loss to be included.

Table 1. Exclusions from the Accident Database

3. Aircraft accident deceleration models

3.1 Kirkland's deceleration model

Kirkland (2001), repeated in Kirkland et al. (2003), developed an acceleration model for overrun accidents as part his overall approach to modelling accidents (Kirkland, Caves Humphreys & Pitfield, 2004). He showed that acceleration (a) could be derived from,

$$a = (v^2 - u^2)/2s \quad (1)$$

where,

a = acceleration, metres per second squared

v = final velocity, metres per second

u = initial velocity, metres per second

s = displacement, metres

This average acceleration was calculated as a complete record of an accident's deceleration was not available. He noted that a number of factors affect deceleration: the type of ground that is traversed and its friction surface, the aerodynamics of the aircraft such as drag and lift, the braking and reverse thrust and the initial speed. Unfortunately, Kirkland (2001) noted that flight recorder information in most cases is not detailed enough to determine the level of braking and thrust although in some cases it is known that no brakes were used. In addition, only broad distinctions in ground type are made. It can probably be assumed, however, that aerodynamic braking effects maybe negligible in the landing overrun case because aircraft are generally at the low end of the speed curve when the runway surface is left. However, for take-off overruns this is not likely to be the case for either rejected take-offs or take-off overruns where no rejection was attempted.

He then regressed the derived values of acceleration (a) on u to derive a β_1 estimate and a β_0 where the latter could be adjusted to reflect different categories of overrun.

He found that for the reference class of wet or dry grass or pavement

$$\begin{aligned} a &= \beta_0 + \beta_1 u \\ a &= -0.0185 - 0.06749u \end{aligned} \quad (2)$$

with $\beta_1 = -2.788$ for mud and gravel giving a final adjusted $\beta_0 = -2.807$

and $\beta_1 = -8.518$ for obstacles/water giving an adjusted $\beta_0 = -8.537$. Goodness-of-fit is shown by $R^2 = 0.558$ with $F = 29.453$.

However one criticism of this model is that it gives acceleration as a constant rate subject to some adjustments to the intercepts. It would be an improvement if acceleration could be calculated for different parts of the wreckage path. It also applies to all types of overrun.

3.2 Improving deceleration models: Data shortcomings

Although wreckage path distance is recorded from the point of first impact (POFI) and an estimate is given for the velocity at the POFI in the database used in Wong (2007), this only allows the calculation of deceleration over the whole wreckage path distance. Influences on deceleration may be gauged from the slope of the wreckage path and the surface, which is recorded (if is not a missing value) for different parts of the total wreckage path length, determined by events such as hitting obstacles, defined as anything significant enough to cause an aircraft to alter course or if it enters water.

If initial velocity could be estimated for each of these lengths then the influence on deceleration, which would not be a constant, could be seen as the aircraft travelled from POFI to its final wreckage x , y , and z location. In fact, it can only be calculated for a limited number

of cases because of omissions in the data collected and recorded in the accident dockets. So an obvious improvement still cannot be made due to data deficiencies.

Note that the wreckage location x for take-off overruns is measured from the start of roll to final location for take-off overrun accidents. For landing overruns it is measured from the landing threshold. For the vast majority of cases, therefore, the aircraft spend some time on the runway before exiting to a wreckage path so runway characteristics can be relevant.

3.3 Improving deceleration models: Bivariate analyses, take-off overruns (TOOR)

A variety of X variables (see Table 2) can be investigated for their role in causation in a bivariate regression analysis, but many of the results are disappointing, in part, because of the paucity of the number of cases with recorded data, especially on speed at the POFI which prevents the calculation of deceleration.

Continuous	Categorical	Binary Dummy
wreckage location x	crash control (3)	collision
wreckage location y	light(4)	go round or take off abort
POFI x	rain (4)	icing
POFI y	runway braking condition (6)	snow
runway exit x	runway condition (3)	
runway landing/take-off distance available	slope (2)	
aircraft weight	wreckage path surface type(5)	
temperature		
fuel load		
obstacles hit		
wreckage path lengths (up to four)		
POFI velocity		
crosswind		
headwind		
tailwind		

Table 2. Variables for Aircraft Accident Models

Categorical variables measure the wreckage path surface, (grass, mud, gravel or paved – referenced, and another category). This last category represents the most extreme cases from the database. The notes reveal that it includes cases that encountered mud and trees, crashed into wooded terrain or residences or hit embankments. Particular cases are recorded as encountering rough terrain and a frozen creek and “struck trees 7 ft. below summit of hill, airborne for 700 ft., then slid 300 ft. down to bottom of hill on snow.” Other categorical

variables represent wreckage path slope (positive, negative or zero slope with one case of slope recorded in degrees), light (day – reference, dawn, dusk or night), rain (none-reference class, or light, moderate or heavy), snow (a binary dummy) and icing (also a binary dummy). Other variables investigated are temperature, aircraft weight, tail, head or crosswind speed (headwind was significant with $b_i = -0.948$), the number of obstacles hit (but where frangibility is not accounted for), crash control, the ability of the pilots to control the aircraft (full control - reference, partial control or none), runway condition (normal- reference, wet, contaminated), and runway braking conditions (excellent –reference, good, fair, poor, slippery, none). However, a few variables gave some plausible and significant results in a bivariate analysis and all were significant at the 95% level. These included the initial velocity at the POFI ($b_i = -0.075$), and whether the take-off was aborted ($b_i = 11.054$), although some of the categorical coefficients have rather high absolute values. These may still be understandable given the simple arithmetic impact on acceleration via the intercept.

3.4 Improving deceleration models: Multivariate analyses, take-off overruns

An OLS regression on deceleration in ft. per s. squared was run using headwind (ft. per s.), whether the flight was an aborted take-off and the velocity at the POFI as explanatory variables. Figure 1 illustrates the basic data. The relative outlier observed at the bottom right of the scatter is a Gates Learjet instructional flight at Waco, Texas in 1984. This was a go round that resulted in a very short wreckage path after the accident that was at relatively high speed and so decelerated sharply. However, its contribution to the regression results is not judged to be overwhelming by Cook's distance and as the number of observations is small it was retained.

These regression results are disappointing so after experimentation a final regression was derived that explained deceleration in terms of whether the runway was wet or contaminated, whether there was light rain and whether the flight was an aborted take-off as well as the headwind speed. These results are shown in Table 3 along with collinearity diagnostics where this topic was also examined by examining simple correlations. A negative impact on acceleration may be expected for an aborted take-off as the pilots will deploy spoilers and reverse thrust in a deliberate attempt to stop. The negative impact of headwind is self-explanatory but the runway characteristics can only be an indication of the ground conditions as deceleration is measured after the runway has been left. The positive impact of light rain may be because of traction on wet ground.

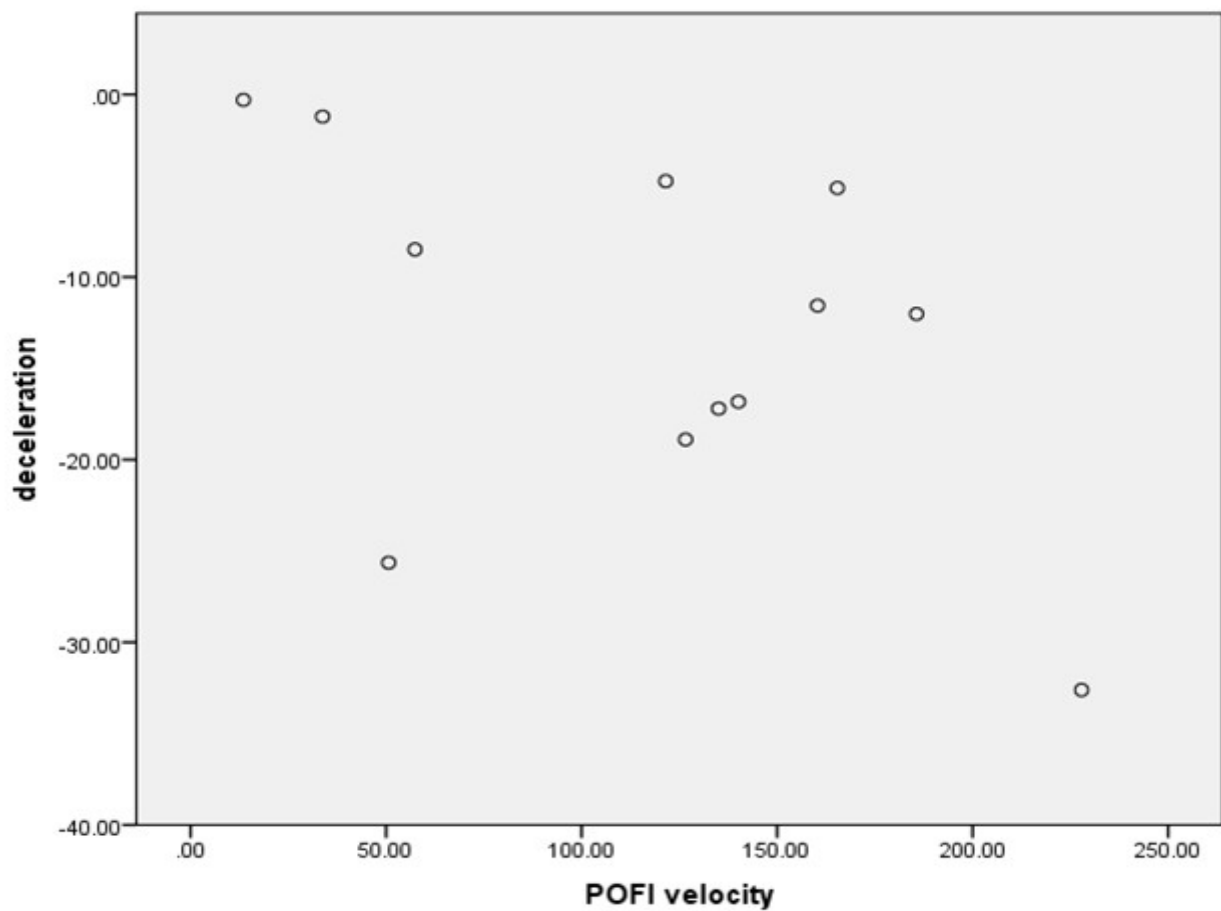


Figure 1. Deceleration against POFI velocity, TOOR accidents

Source	SS	df	MS
Model	433.240	5	86.648
Residual	66.752	2	33.376
Total	499.992	7	

Model	Coef.	Std. Error	Standardised Coefficient Beta	t	Sig	Collinearity Tolerance	Statistics VIF
(constant)	17.469	11.056		1.580	0.255		
wet runway	-50.837	16.110	-2.127	-3.156	0.087	0.147	6.804
contaminated runway	-29.488	9.426	-1.806	-3.128	0.089	0.200	4.991
light rain	42.036	11.856	2.659	3.546	0.071	0.119	8.423
headwind	-3.796	1.210	-1.876	-3.137	0.088	0.187	5.354
aborted take-off	-17.157	9.958	-0.718	-1.723	0.227	0.385	2.600

Number of obs. = 7; $F(5,7) = 2.596$; Sig = 0.301; R-squared = 0.866; Adj R-squared = 0.533; Std. Error = 5.772

Table 3. Regression, Deceleration against runway condition, light rain, headwind and aborted take-offs.
TOOR accidents

These results suggest a reasonable level of explanation but the results overall are not significant as the number of observations is too small. Where Kirkland (2001) found he was able to identify influences of ground type and obstacles here the constant could be adjusted by the coefficient for runway surface and contaminated surface, showing that both have a negative effect by comparison with normal surfaces, as well as the coefficient for an aborted take-off. Note that the value of R^2 is superior to Kirkland's 0.558 at 0.866, but he was dealing with all overruns and had a larger number of observations. The results here are not significant overall.

Deceleration can be given for normal runway conditions by

$$= 17.469 - 3.796 \text{ Headwind} \quad (3)$$

and when the runway surface is wet,

$$= -33.368 - 3.796 \text{ Headwind} \quad (4)$$

when it is contaminated

$$= -12.019 - 3.796 \text{ Headwind} \quad (5)$$

when it is raining lightly

$$= 59.505 - 3.796 \text{ Headwind} \quad (6)$$

and when the flight is an aborted take-off

$$= 0.312 - 3.796 \text{ Headwind} \quad (7)$$

It is hoped that significant overall results may be obtained for a larger sample of landing overrun accidents. These results in this section are marred by a low number of cases often arising from missing data on speed at the POFI.

3.5 Improving deceleration models: Bivariate analyses, landing overruns (LDOR)

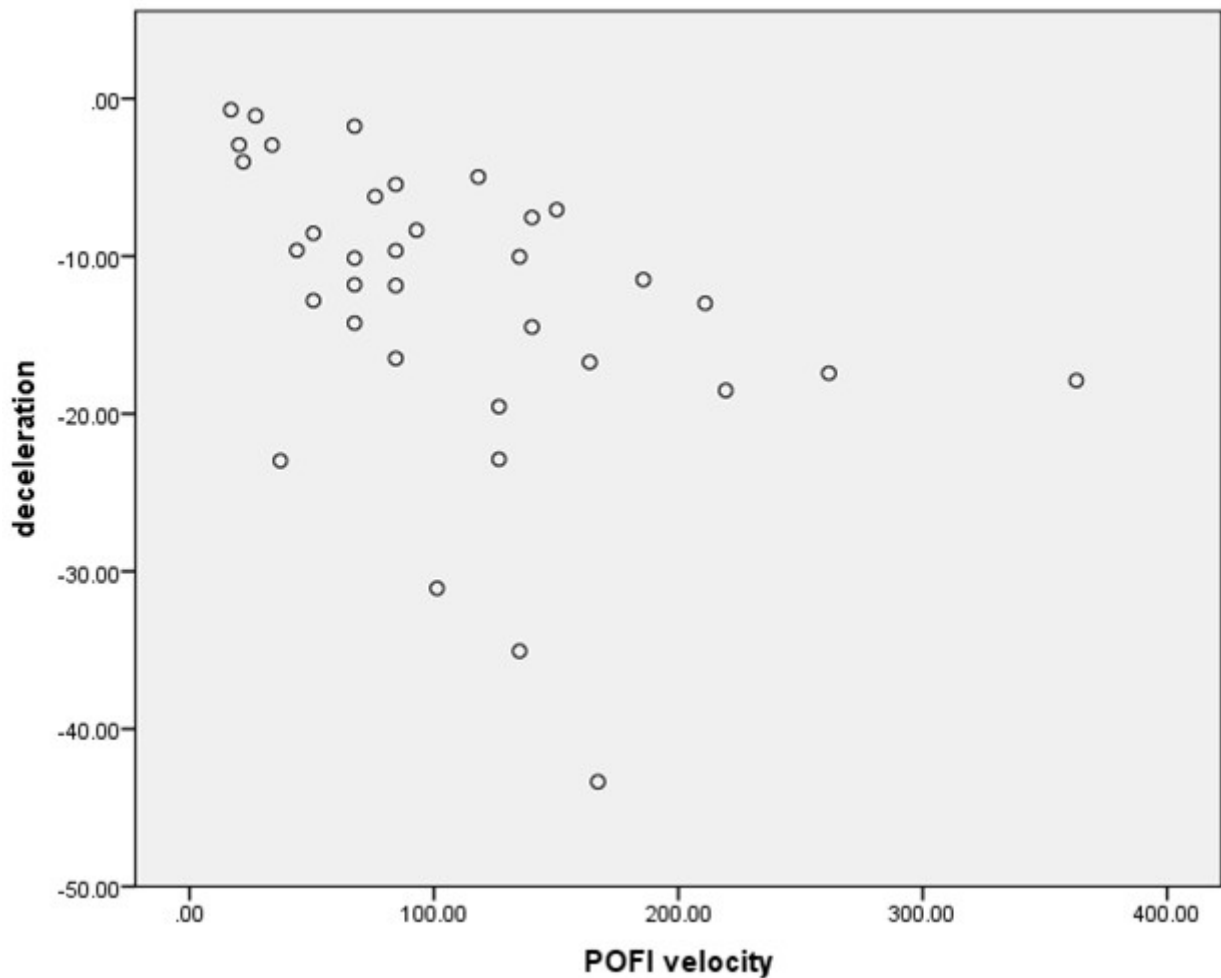


Figure 2. Deceleration against POFI velocity, LDOR accidents with two outliers removed

Figure 2 shows acceleration against POFI initial velocity for landing overruns. It is noteworthy that this class of accidents has a lower initial speed and a shorter wreckage path on average than take-off accidents as would be expected. The mean u is 38.0 ft./s. by comparison to 59.1. The wreckage path mean is 697.2 ft. rather than 987.6. As with the analysis of take-off overruns, this analysis started with an examination of bivariate relationships with deceleration. It was hoped that this analysis would assist in the building of a multivariate model that yielded good explanation that was populated by meaningful X variables from those shown in Table 2.

The only variables that yielded t statistics over 2.00 were POFI velocity, rain and runway condition. The respective t values were -2.773, -2.013 for light rain by comparison to no rain, and -2.436 for wet runways by comparison to normal. The coefficients were -0.125, -16.952 and -23.330.

3.6 Improving deceleration models: Multivariate analyses, landing overruns

A variety of attempts to produce significant multiple regression results based on the bivariate results foundered. This was both because of a lack of significance of noted explanatory variables, but also because of low overall goodness-of-fit and insignificance. In addition, tests of normality and their plots indicated that the regression residuals were not normally distributed.

These experiments suggested that there are elements of the data that could be considered as outliers. The philosophy of the treatment of outlier is not a subject for discussion here but progress was made when two cases were excluded. The first of these has an extreme deceleration figure and was a Learjet go-round at Roanoke, Virginia, in March 1989. This aircraft overran twice. The first time it went off the end of a runway after the lift dumping and thrust reverse systems failed but climbed away from a baulked-landing. The second time it landed and slid 200 ft. off the end of the runway because the undercarriage had fallen off in the initial overrun when it hit a dirt berm at the end of the grass overrun.

The second also has a high deceleration value and is a DC-9 at Sioux Falls, South Dakota, in December 1983. The aircraft touched down normally about 1,000 feet down from the approach end of the runway and struck a snow plough approximately 2,200 feet from this end. The aircraft had just started to decelerate from the landing speed at the time of impact which led to the separation of the right wing. It came to rest 4,125 feet from the start of the runway off to the left side. The x, y locations are 4,125 and 102 ft. These cases both point to difficulties with the recorded data on distances and speeds that allows comparison of disparate accident occurrences.

The data is shown in Figure 2.

Table 4 shows the multiple regression results.

Attempts to produce a multivariate equation resulted in a $R^2 = 0.483$, with significant influences of the POFI velocity ($t = -2.602$), its square ($t = 1.867$), partial pilot control rather than full ($t = 2.177$) and the first part of the wreckage path covered in grass by comparison to paved ($t = 2.420$). Another variable in the equation which was not as significant is the wreckage path surface over the first wreckage path length described as snow covered trees etc. ($t = 1.223$). As this categorical variable denotes a variety of types of wreckage path, it was retained.

These results have a reasonable level of fit, are significant overall and the tests on the residuals suggests they are normally distributed. The coefficients also have signs that seem to make sense.

Source	SS	df	MS
Model	1,479.477	5	295.895
Residual	1,583.711	27	58.656
Total	3,063.188	32	

Model	Coef.	Std. Error	Standardised Coefficient Beta	t	Sig	Collinearity Tolerance	Statistics VIF
(constant)	-9.118	4.532		-2.012	0.054		
POFI velocity	-0.142	0.054	-1.038	-2.602	0.015	0.120	8.303
POFI velocity ²	0.0003	0.0002	0,725	1.867	0.073	0.127	7.871
Pilot partial control	6.816	3.132	0.325	2.177	0.038	0.858	1.165
Wreckge path surface, grass	7.430	3.070	0.385	2.420	0.023	0.755	1.324
Wreckage path surface, snow covered trees etc.	6.393	5.227	0.191	1.223	0.232	0.787	1.270

Number of obs. = 32; F(5,27) = 5.045; Sig = 0.002; R-squared = 0.483; Adj R-squared = 0.387; Std. Error = 7.659

Table 4. Regression, Deceleration against POFI velocity and its square, pilot control and wreckage path surfaces. LDOR accidents

Deceleration can be given for normal runway conditions and other conditions based on the data in Figure 2 by

$$= -9.118 - 0.142 \text{ POFI velocity} + 0.00029 \text{ POFI velocity}^2 \quad (8)$$

and when the pilot has partial control by comparison to full,

$$= -2.302 - 0.073 \text{ POFI velocity} + 0.00029 \text{ POFI velocity}^2 \quad (9)$$

when the first section of the wreckage path is grass

$$= -1.688 - 0.073 \text{ POFI velocity} + 0.00029 \text{ POFI velocity}^2 \quad (10)$$

and when the first section of the wreckage path is as bad as it can be by comparison to paved

$$= -2.725 - 0.073 \text{ POFI velocity} - + 0.00029 \text{ POFI velocity}^2 \quad (11)$$

4. Conclusions

Wong (2007) noted that the major data limitations limiting analysis of aircraft accident data on a comparable basis concerned missing data, poor data quality and inherent measurement difficulties and his comments are repeated below.

The NTSB accident investigation records principally consist of a number of standard forms and reports. Even within these standard areas of interest, it is extremely rare that every field is filled in. Just a small proportion of data fields are systematically recorded for every accident. The amount of missing fields in the database is therefore high, restricting the number of parameters that could be analysed.

The docket files contain mostly information which the accident investigators deemed relevant to an accident's occurrence. Out side of this judgement, few potential risk factors are included. This is a major handicap in building a data base that consistently and systematically records a set of risk exposure parameters.

Erroneous or conflicting information within the same docket is not uncommon. One example is that the wreck age location diagram provided does not match the text description given.

The measurement of certain parameters suffers from inherent ambiguity in the aviation industry. A prime example is runway condition. There simply has not been an agreed industry standard on reporting runway conditions and determining its relationship with runway friction and aircraft braking performance (De Groh, 2006; FAA, 2006). The current industry approach is solely mostly on pilots' subjective reporting. However, runway surface conditions may change rapidly according to precipitation, temperature, usage and runway treatment so actual conditions may differ significantly from that which was reported (FAA, 2006). Icing conditions too are known to be difficult to determine despite their important impact on aircraft performance (Winn, 2006).

The reporting of meteorological conditions in general is not as straight forward as it seems. The weather measured from ground stations may vary significantly from that experienced by the accident flight (Jerris, Gerafolá, Dagen & Brady, 1963), especially if the weather station is located far from the accident location, although the latter is only common among very remote airports. Another difficulty lies with the dynamic nature of meteorological conditions. Wind strength and direction may constantly change during the course of an approach. It may not always be clear as to which reading is most relevant.

It has to be agreed that difficulties with data prevents a more detailed estimate of acceleration in the first place and that inconsistencies in the available data considerably reduce the number of observations that the models are based on by comparison with the initial number of such

accidents in the database. Indeed, there is an instance where the lack of comparable data suggests that particular cases are excluded from the analysis.

However, some of the presented results are significant despite these shortcomings. It is clear that if this sort of work is to progress data collection practices must improve in detail and consistency. This was suggested by Wong (2007) and the findings of this paper support this suggestion. If these improvements are forthcoming, deceleration may be better understood and the understanding of the wreckage location of aircraft accidents can be improved. This then gives guidance on appropriate runway safety areas.

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